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Title:	AS 65 Close Out: Verification Using Neutron Multiplication at Spent Fuel Repositories
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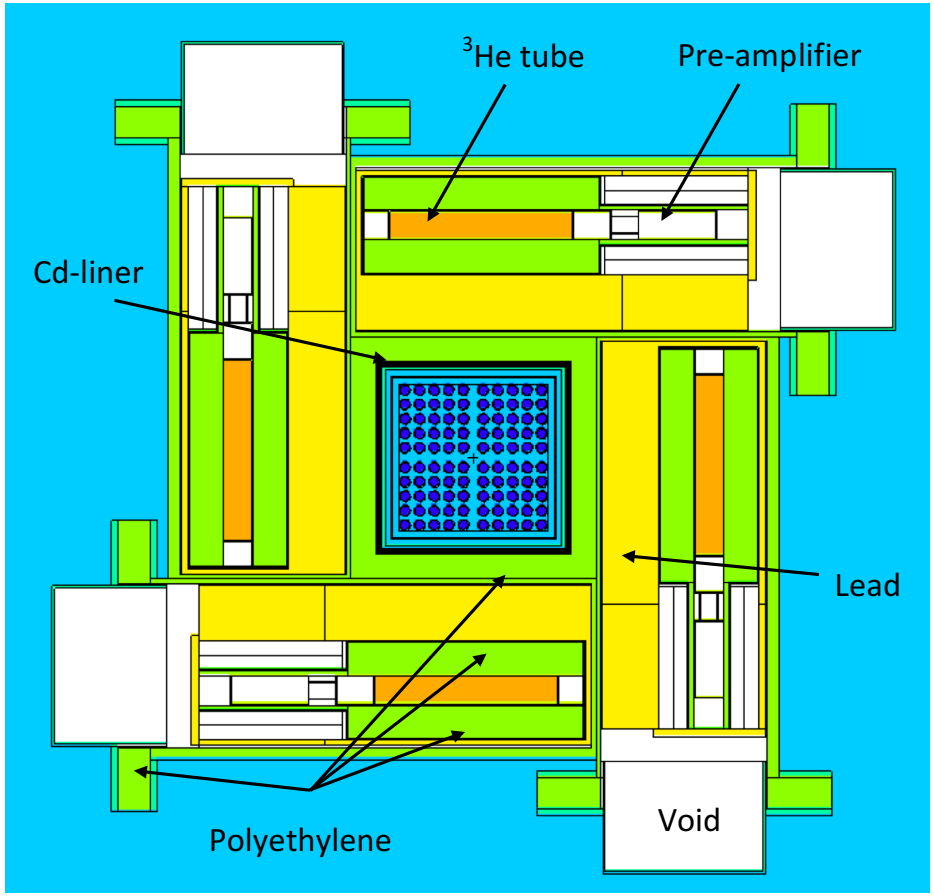
AS 65 Close Out: Verification Using Neutron Multiplication at Spent Fuel Repositories

Stephen J. Tobin in collaboration with a multitude of researchers over many years



Background of IAEA Support Program in Repository Context

- Development of Safeguards for Geological Repositories (SAGOR, 1994-2004)
- Program for the Application of Safeguards to Geological Repositories (ASTOR, 2005-2017)
  - ASTOR Group Report 2011-2016, "**Technologies Potentially Useful for Safeguarding Geological Repositories**," International Atomic Energy Agency, STR-384, Vienna, Austria 2017

Three authors of this report were both (a) on the NDA Focus Group of ASTOR and (b) involved in Action Sheet 65

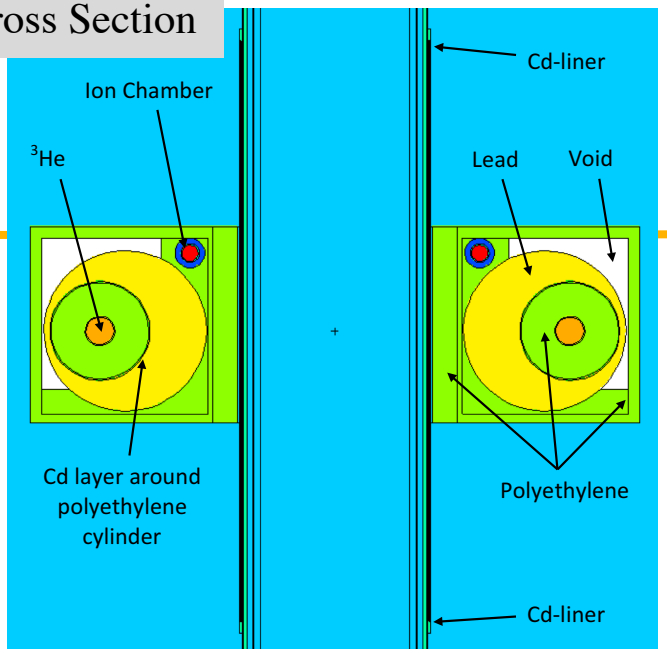
- Stefano Vaccaro, Euratom
- Tapani Honkamaa, STUK
- Steve Tobin, DOE-LANL, STUK-LANL

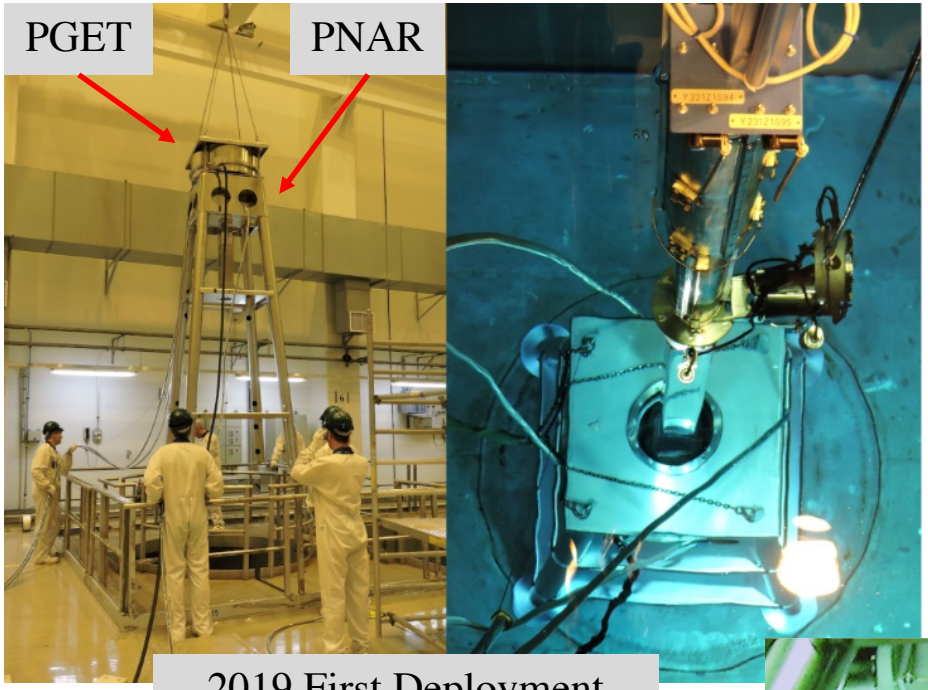
Recommendation of the ASTOR's NDA Focus Group for the Spent Fuel Assembly NDA System

1. Capability to detect individual pins, even though it is recognized that pin level detection might not be possible for all assembly fuel types and for all burnup and cooling time scenarios.
2. Capability to verify that the declared assembly is consistent with measured signatures: Enough information is provided in the declaration of each assembly to predict, within useful limits, some measurable signatures from each assembly. Once predicted, a comparison between expectation and measurement is possible and recommended.
3. Capability to measure assembly neutron multiplication: The neutron multiplication of an assembly can be measured with the neutron signal. Furthermore, this multiplication can also be calculated from the declaration. Multiplication is singled out in this list for its close connection to the presence of fissile material and because it is a bulk property of the assembly.
4. Robustness, low maintenance and low false alarm rate must all be properties of the NDA system.
5. System should be difficult to trick with pin substitution … the aggregate NDA system needs to make well-designed pin replacement extremely difficult to plausibly/usefully perpetrate.
6. Capability to measure the total weight :

The Finnish NDA system (PGET + PNAR + Weight) satisfy all 6 recommendations; Action Sheet 65 directly assisted with #2. PNAR satisfied #3.

Images of the Finnish System

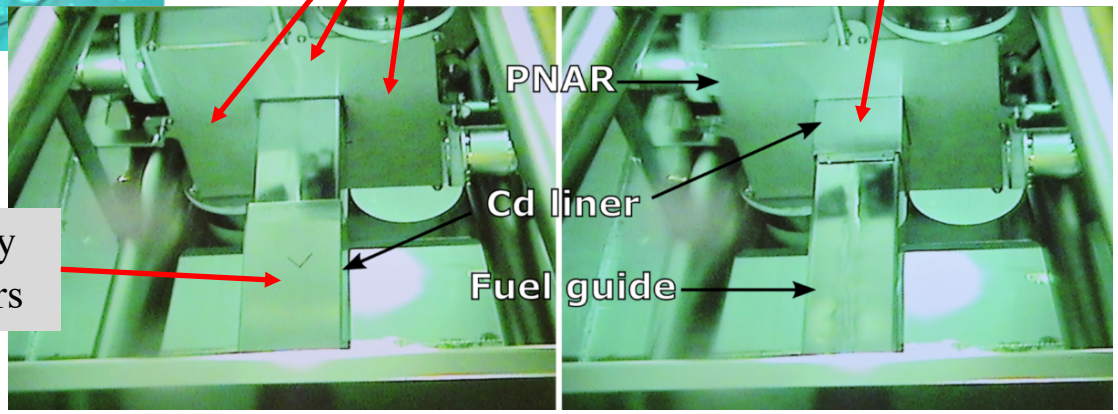




2019 First Deployment

^{3}He Detectors

Cd-liner between Fuel and Detectors



All photographs are from STUK

Cd-liner away from Detectors

The Basics of PNAR

- Conceptually PNAR can be though of as “interrogating the assembly with thermal neutrons from all around the assembly”

- PNAR Ratio = $\frac{Neutron\ Counts\ for\ \textbf{\textit{High}}\ Multiplying\ Setup\ (HMS)}{Neutron\ Counts\ for\ \textbf{\textit{Low}}\ Multiplying\ Setup\ (LMS)}$

$$= \frac{Neutron\ Source\ Term * \varepsilon_{HMS} * M_{HMS}}{Neutron\ Source\ Term * \varepsilon_{LMS} * M_{LMS}}$$

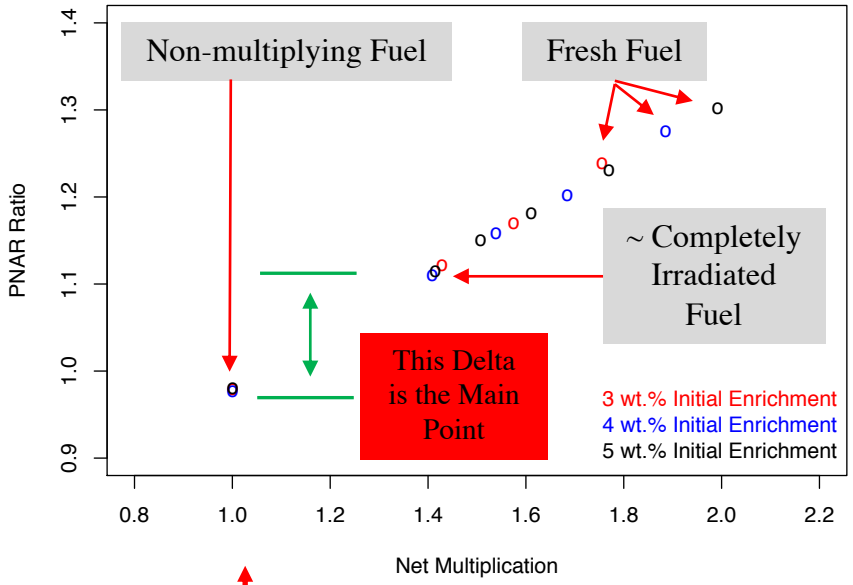
Specific to the Finnish instrument

$$= \frac{\varepsilon_{HMS} * M_{HMS}}{\varepsilon_{LMS} * M_{LMS}} \quad where \quad \frac{\varepsilon_{HMS}}{\varepsilon_{LMS}} = 0.97 \text{ due to water vs. liner}$$

$$= 0.97 * \frac{M_{HMS}}{M_{LMS}}$$

Multiplication definition: the total number of neutrons that exist in a sample divided by the number of neutrons that were started.

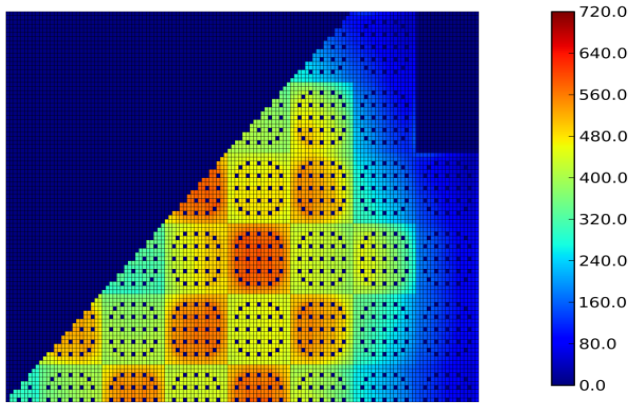
Benchmark … Putting it all Together



Simulated Assemblies (NGSI–SF)

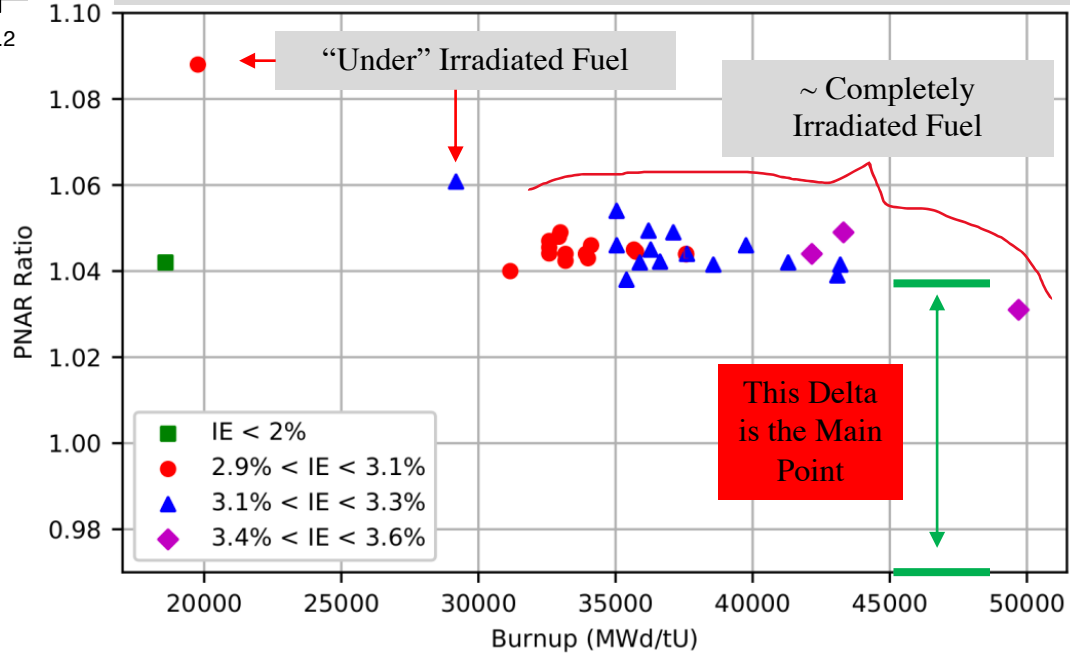
Measured Assemblies

Part of why we expect variation in multiplication



Simulated Power within PWR Core, Trellue et al.

Topi Tupasela, "*PNAR Measurement in Olkiluoto SFS 2020*"



PNAR in Service to the Nuclear Regulator

- Anomalous assemblies are a particular issue for regulators
  - Anomalous assemblies, generally … **were removed from the reactor for an atypical time interval before final cycle** resulting in …
    - Abnormal **actinide content**, as the typical neutron capture process from ^{238}U “on up” is altered
    - Abnormal **gamma emission**, as "extra decay" takes place while assembly is not in the reactor
    - Algorithms based on the **cooling time** are generally formulated with assembles that never “sit out” reactor cycles
- The PNAR signal will be less sensitive to anomalous assemblies, because the reactor operator, for safety and economic reasons, accurately tracks and “burn up” each assembly
  - The reactor operator cares little about the gamma emission and spontaneous neutron emission from an assembly; while, **operators care very much about the multiplication of each assembly**

AS65/PNAR Close Out Summary

- AS65 directly enabled a recommendation of the ASTOR's NDA Focus Group: "verify that the declared assembly is consistent with measured signatures"
- PNAR satisfied the "Capable to measure assembly neutron multiplication"
- The PGET + PNAR + Weight measurement satisfy the remaining recommendations:
  - "Detect individual pins" **(PGET)**
  - "Robustness, low maintenance and low false alarm rate" **(System and depends on implementation)**
  - "Difficult to trick with pin substitution" **(System)**
  - Able "to measure the total weight" **(Balance)**